Predicting Vapor Intrusion Risks in the Presence of Soil Heterogeneities and Anthropogenic Preferential Pathways

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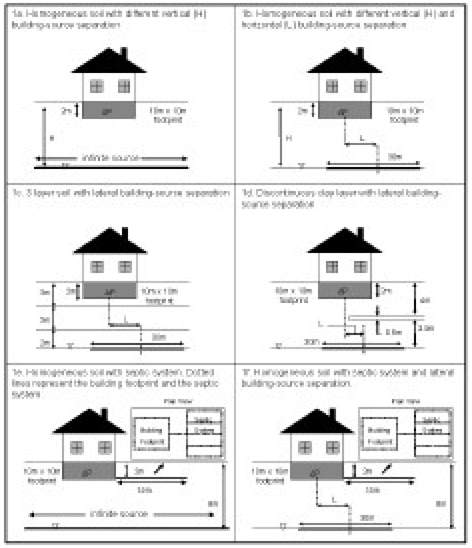
Abstract

Designing and implementing sampling plans to characterize vapor intrusion (VI) risks can be difficult. In addition to different jurisdictions having different requirements, the literature (and regulatory guidance documents) contain conflicting data and recommendations. In general, scientific understanding lags behind the need to assess risks; consequently, tools to assist vapor intrusion site characterizations are thus far limited in number.

In response to the need for additional science and tools to guide vapor intrusion characterizations, a three-dimensional numerical model was developed to examine various vapor intrusion scenarios. The effects of site-specific geological and man-made features (e.g., source-receptor separation, existence of potential preferential pathways) on vapor intrusion were investigated. These results confirm that soil gas measurements by themselves are not reliable indicators of vapor intrusion risk. Moreover, characterization of soil heterogeneity is important for developing accurate conceptual site models.

Scenarios

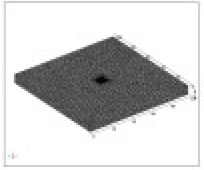


Notes:

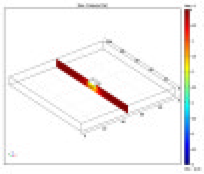
- The EPA indoor air standard (10^{-6} risk) = 2.2E-2 ug/m^3
- Source concentration is Rhode Island Department of Environmental Management Industrial Cleanup Standard (GB Standard).

Research Approach

A computational fluid dynamics package, Comsol Multiphysics, is used to create a 3D finite element model to evaluate vapor intrusion using conventional fate and transport processes. The model first solves soil gas continuity equation (Equation 1) and then couples it with the chemical transport equation (Equation 3). The indoor air concentration is determined analytically using Equation 4.

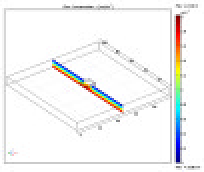


Model Domain 100m x 100m



Model Solution for Pressure Profile

(Equation 1)



Model Solution for Chemical Concentration Profile

(Equation 3)

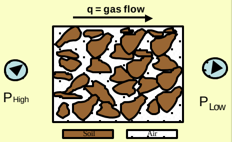
Equation 1:
Soil Gas Continuity

Note: Equation 1 is valid for gas flow in soils where slip flow is negligible (sands and gravels). For very fine-grained materials, Darcy's Law (Equation 1) may underestimate flow (Massman, 1989).

$$q = \frac{k \cdot r_g \cdot \nabla f}{m_g} \qquad f = gz + \int_{P_0}^{P} \frac{\nabla P}{r}$$

$$C_{indoor} = \frac{A_{ck} J_T}{A_e V_b + Q_{ck}}$$

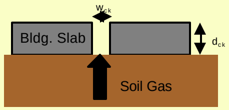
Where:
k = Intrinsic permeability (L^2)
r_g = Density of soil gas (M/L^3)
m_g = Dynamic Viscosity of soil gas ($M/L/t$)
g = gravitational acceleration (L/t^2)
P = Pressure of soil gas ($M/L/t^2$)
z = elevation (L)



Equation 2:
Pressure Drop through Crack

$$\Delta p = \frac{12 \cdot Qck \cdot m_g \cdot d_{ck}}{w_{ck}^{3}} \qquad Q_{ck} = Q_{CER}$$

where:
Δp = pressure drop across crack ($M/L/t^2$)
w_{ck} = Width of crack (L)
d_{ck} = Depth of crack (L)
Q_{CER} = Modeled soil gas flow rate through characteristic entrance region
Q_{ck} = Soil gas flow rate through crack into building (L^3/t)

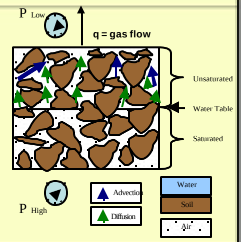


Equation 3:
Chemical Transport

$$J_T = q \cdot C - D_{ig} \nabla C$$

$$D_{ig} = d_i^{air} \cdot \frac{h_g^{10/3}}{h_T^{2}}$$

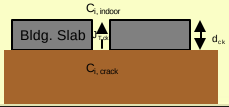
Where:
J_T = Bulk mass flux of 'i' ($M/L^2/t$)
C = Concentration of 'i' in soil gas (M/L^3)
D_{ig} = effective diffusivity coefficient of 'i' in soil gas phase (L^2/t)
d_i^{air} = molecular diffusion coefficient (L^2/t)
h = porosity; t=total, g=gas-filled (L^3/L^3)



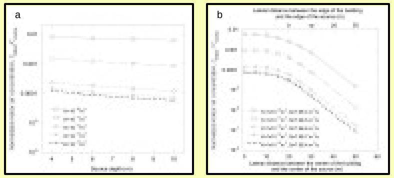
Equation 4:
Indoor Air Concentration

$$C_{indoor} = \frac{A_{ck} J_T}{A_e V_b + Q_{ck}}$$

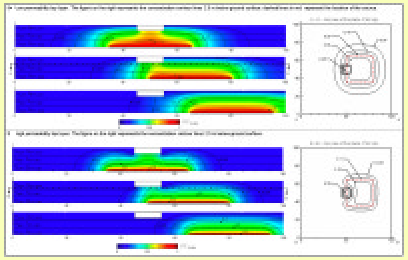
Where:
$J_{T,ck}$ = Bulk mass flux of 'i' through crack ($M/L^2/t$)
C_{indoor} = Concentration of 'i' in the indoor air (M/L^3)
Q_{ck} = Soil gas flow rate into crack (L^3/t)
A_e = Air exchange rate of building (1/t)
V_b = Volume of building (first floor volume is commonly used) (L^3)



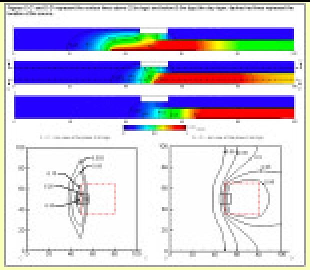
Results



Effect of vertical (a) and lateral (b) building:source separation.

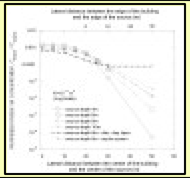


Effect of soil layers and lateral separation on soil gas profiles.



Effect of lateral separation and discontinuous clay layer on soil gas profiles.

Clay layer prevents vapor migration to atmosphere, which results in elevated subsurface concentrations beneath it.



Combined effect of lateral and vertical source separation.

Deeper sources can result in higher indoor air concentrations (as compared to shallower sources) at lateral separation distances > 10 m (building edge to source edge).

Conclusions: Geological heterogeneity and man-made preferential pathways can strongly influence indoor air concentrations. Indoor air concentration depends on local soil gas contaminant concentration and soil gas advection. Both are sensitive to geological factors. Commonly used 100 ft (30 m) lateral separation criterion is often suitable, but not always protective.